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GPS Amplitude Scintillations over Kampala, Uganda, During 2010-2011

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Abstract

This study characterizes equatorial scintillations at L1/L2 GPS frequency over Kampala (0.30°N, 32.50°E, mag. lat. 9.26°S), Uganda, on different time scales during the minimum and ascending phases of solar cycle 24 (2010-2011). Of all the days investigated, 25 October 2011 recorded the highest occurrence of scintillation, and it was attributed to geomagnetic storm occurrence. We used the data of 25 October to generate plots of the elevation angle and S_4 index against local time on a satellite-by-satellite basis, with a view to distinguishing satellites links whose signals were impaired by ionospheric irregularities from those impaired by multipath. Conclusively, GPS amplitude scintillations over Kampala occur predominantly during post sunset hours and decay around midnight. Equinoctial months recorded the highest occurrences of scintillations, while June solstice recorded the least. Scintillation occurrences also increase with solar and geomagnetic activity.

Key words: ionospheric scintillation, Africa, equatorial region, irregularities, solar cycle 24.

1. INTRODUCTION

The progressive efforts made over the past years to support global understanding of the underlying physics behind the formation of ionospheric irregularities are still being challenged by data gaps, due to uneven global distributions of ionospheric sensors, particularly in the equatorial region of Africa (Akala *et al.* 2014). However, the situation is being assuaged by the recent concerted installations of instruments at many locations across Africa, upon which ionospheric results from African sector are now presented to the scientific community.

One of cardinal implications of ionospheric irregularities is scintillation, which is the rapid fluctuations in the amplitude and/or phase of radio signals that transverse the F region of the ionosphere. Typically, scintillation is measured by the S_4 index − the standard deviation of the factor $I/\langle I\rangle$ over a 60 s period, I being the received signal, and $\langle I\rangle$ its average value. Scintillation is a post sunset event in the equatorial region and can occur at any time of the day at the poles. Studies revealed high prevalence of scintillation activities at high latitudes, weak at mid latitudes and intense at the equatorial region (Aarons 1982, Basu *et al.* 1988, Akala and Doherty 2012). At high latitude, scintillation is mainly associated with large scale plasma structure. In the equatorial region after sunset, abrupt changes in ionospheric conductivity along magnetic field lines cause large scale plasma bubbles to form at the bottom side of the ionosphere, to later rise to greater heights to cause scintillation of the trans-ionospheric radio signal.

There has been global reliance of man on space-based technology in recent years. Consequently, efforts aimed at mitigating the impacts of scintillations on man-made systems are currently a core area of research. For instance, ionospheric scintillations are known to degrade the performance of the satellite based communication and navigation systems (Akala *et al.* 2011). To this end, the International Civil Aviation Organization (ICAO), *via* its national agencies, is at the vanguard of sponsoring researches that are focused on proffering understanding/mitigations to the impacts of the ionosphere on Global Navigation Satellite Systems (GNSS).

The goal of this study is to characterize equatorial latitude scintillation at L1/L2 GPS frequency over Kampala, Uganda, in East Africa longitudinal sector on daily, monthly and seasonal time scales during the minimum and ascending phases of solar cycle 24. The study also aims at adding to the quantum of documented African equatorial ionospheric scintillations results on global archives, which are prior to now very scanty. These results could be of support towards the development of future physics-based global ionospheric scintillation models.

2. METHODOLOGY

The amplitude scintillation data used for this research was acquired from the SCINDA-GPS station, located at Kampala (0.3°N, 32.6°E, mag. lat. 9.26°S), Uganda. The data sets covers two years (2010-2011). 2010 was a year of minimum solar activity, with average annual sunspot numbers Rz; 18, while 2011 was a year of ascending solar activity (solar cycle 24), with annual sunspot number Rz; 50. In order to reduce multipath effects, only data from satellites with elevation angles greater than 30° were used (Akala *et al.* 2011, 2014). Each one-minute event was characterized by the data from satellite which provided the highest scintillation index. The data sets were grouped into monthly sets. The data sets were further classified into two levels of scintillations: weak ($0.3 \le S_4 < 0.4$) and moderate ($0.4 \le S_4 \le 0.5$).

Furthermore, the determination of the frequency of occurrence of scintillation for any particular level is based on whether or not scintillation at that level was detected during the night. A given night is considered to experience scintillation if the observed scintillation persisted for at least four minutes during the night. The monthly percentage of occurrence at any given scintillation level was then based on the number of nights of the month in which the event at that level was recorded and the number of days of observations during that month (Akala *et al.* 2011).

Finally, we plotted the elevation angles and scintillation index against local time for the GPS data (unfiltered data, including data from satellites with mask angles as low as 5°) on 25 October 2011 on a satellite-by-satellite basis. 25 October 2011 was characterized by intense geomagnetic storm (*Dst*: –132 nT, *Kp*: 7, *i.e.*, maximum daily 3-hourly *Kp* index), and also recorded the highest occurrences of scintillation during the period under investigation. For the sake of comparison, we analyzed the data of 14 October 2011, a geomagnetically quiet day (*Dst*: +2 nT, *Kp*: 1, *i.e.*, maximum daily 3-hourly *Kp* index), with a view to observing the dependence of scintillations on geomagnetic activity.

3. RESULTS

Figures 1 and 2 are the representatives of monthly plots of S_4 index for 2010 and 2011, in: (a) January, (b) April, (c) July, and (d) October. Other months are not shown. The range of the S_4 data was deliberately fixed at 0 to 0.5, so that scintillation effects could also be observed during low solar activity. The range of values of levels of scintillation was discussed in Section 2. Generally, on daily scale, scintillation events were observed mainly during the hours of 20:00-02:00 LT, with no occurrences during the day. Overall, our results are in agreement with earlier observations by Aarons (1982), Basu *et al.* (1988), Dubey *et al.* (2006), and Akala *et al.* (2011). On monthly scale, in

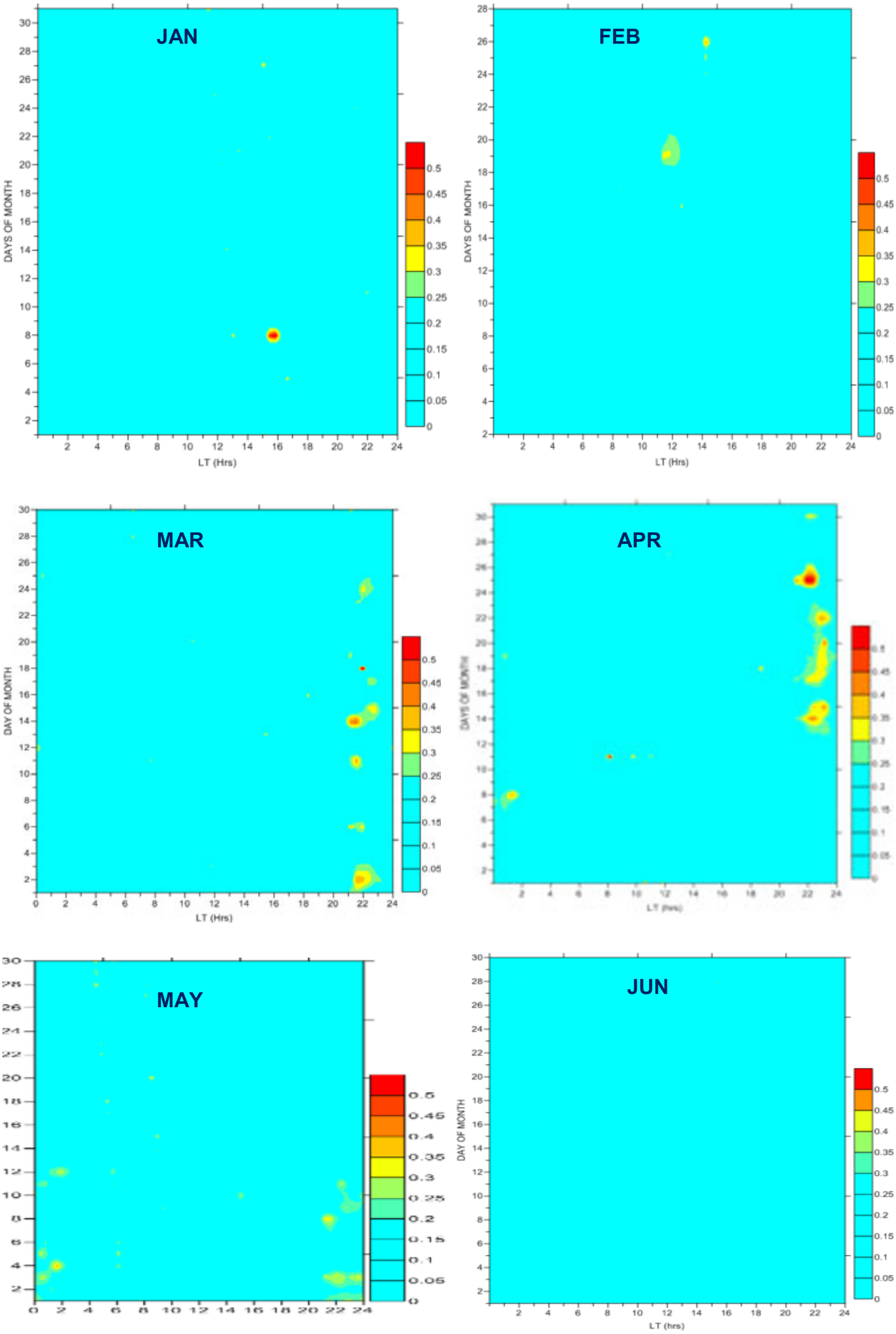


Fig. 1. Caption on next page.

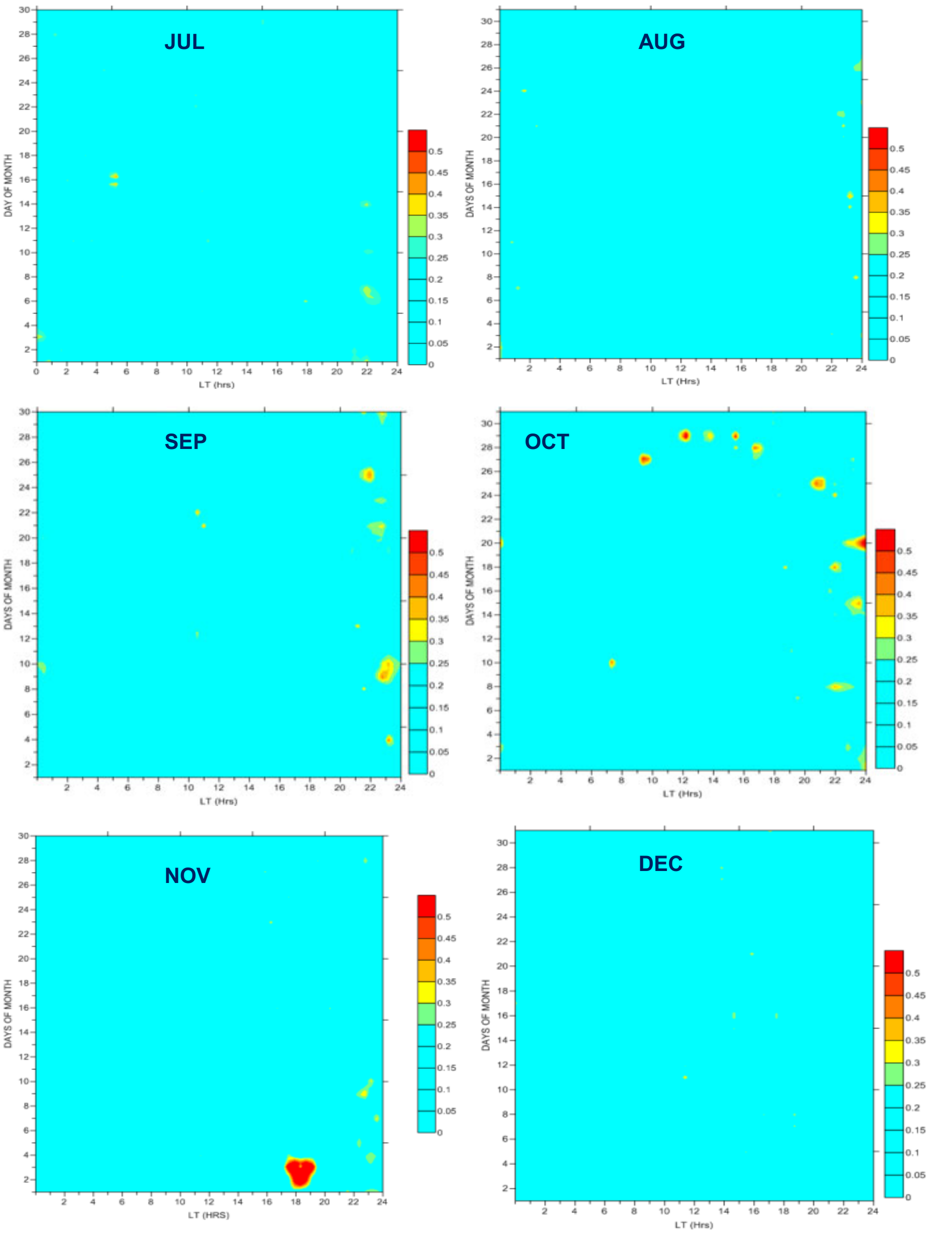


Fig. 1. Monthly colour coded-contour plot of S_4 index for 2010.

2010, moderate scintillation occurrences were observed in the months of March and November. For weak scintillations, the months of February, March, April, September, and October recorded activity, while the months of

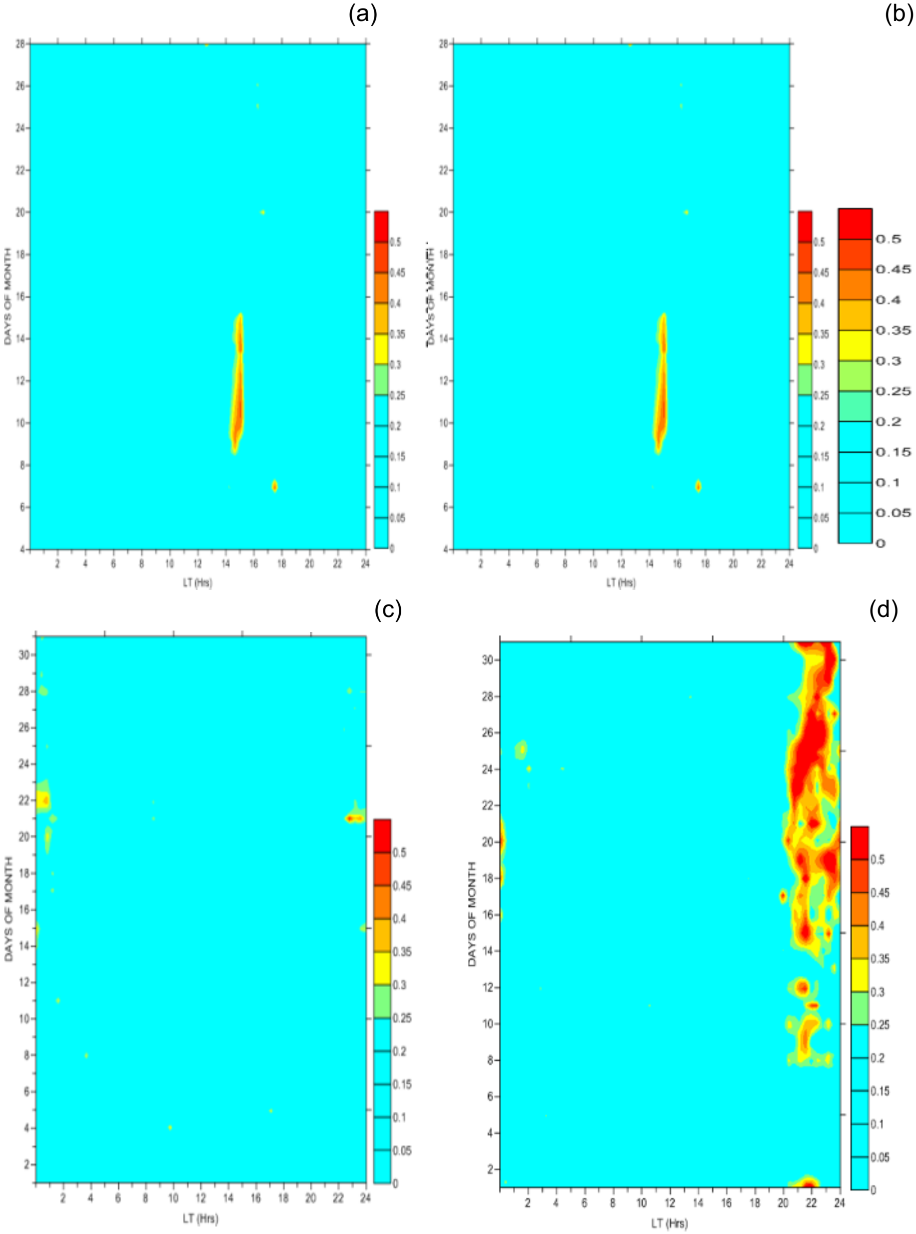


Fig. 2. Representatives of monthly contour plots of S_4 index for 2011: (a) January, (b) April, (c) July, and (d) October.

June and December recorded no activity at both weak and moderate levels. Comparatively, year 2011 showed higher occurrences of scintillation. The months of March, April, May, September, October and November recorded scintillation events at moderate level, while the months of February, June, July, and August recorded only weak scintillations.

Seasonally, in 2010, December solstice (November-January) had few occurrences of scintillation at moderate level, March equinox (February-April) recorded more occurrences of weak scintillations, compared to the moderate level, where June solstice (May-July) recorded more of weak scintillations. September equinox (August-October) recorded only weak scintillation throughout the season. In 2011, during December solstice, scintillations were observed at both moderate and weak levels, although, there were no data for the month of December. March equinox recorded higher occurrences of scintillations at moderate level, while June solstice recorded the least. Generally, equinoxes recorded higher scintillation occurrences than the solstices. These results are in agreement with Paznukhov *et al.* (2012) and Oron *et al.* (2013).

Figure 3 shows the statistics of GPS scintillation occurrences for years 2010 and 2011, respectively. Statistically, in 2010, the month of September had the highest percentage of occurrence of weak scintillation, while the month of May had the least occurrence (Fig. 3a). The months of March and April had the highest occurrence at moderate level of scintillation, while the month of January had the least occurrences, while no scintillations were recorded during the month of February and December. Figure 3b indicates that during 2011, the month of March recorded the highest scintillation activity for weak events, while month of May had the least percentages of occurrences for scintillations. The month of April and October had the highest percentage of occurrence at moderate level, while the month of January and November had the least percentage of occurrences. The months of June, July, and August recorded only weak events.

Figure 4 is representative of the plots of elevation angles and scintillation index against the local time for all satellites visible on 25 October 2011. The day was characterized by intense geomagnetic storm, and also recorded the highest occurrence of scintillations. On 25 October, there were 27 satellites in view of the GPS receiver, 24 GPS satellites and 3 Space Based Augmentation System (SBAS) satellites. The plots were analyzed to determine satellite links with scintillation index due to non ionospheric irregularities and ionospheric irregularities. Data from all satellites, including those at low elevation angles, were used to observe the relationship between elevation angles and scintillation index on a satellite by satellite basis; this relationship was further explored to deduce the effect of scintillation activity due to ionospheric and non ionospheric sources. The results indicate that 6 satellites experienced scintillations as a result of ionospheric irregularities, based on the fact that the signals from these satellites scintillated at high elevation angles. 5 satellites experienced scintillations due to non ionospheric sources

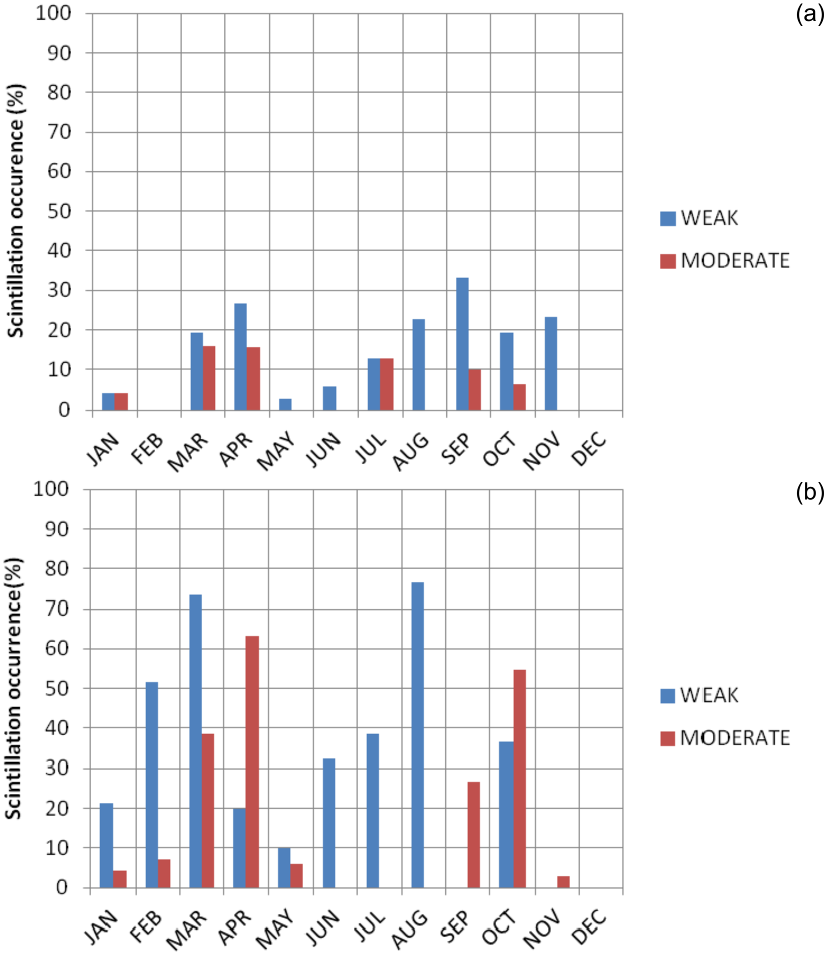


Fig. 3. Monthly frequencies of occurrences foe weak and moderate levels of scintillations: (a) 2010, (b) 2011.

(multipath), based on the fact that the satellites scintillated at low elevation angles. 6 satellites experienced scintillations activities due to both ionospheric and non ionospheric sources, based on the fact that the satellites scintillated at moderate elevation angles. 7 satellites did not experience scintillations, and 3 satellites only appeared briefly. On 14 October 2011, 29 satellites were in view of the GPS receiver: 26 GPS satellites and 3 SBAS satellites. Most of the satellites that scintillated on 14 October 2011 did so at low elevation angles, which suggests that most of the scintillations were caused by multipath. The three SBAS (PRN 120, PRN 124, PRN 128) are geo-stationary satellites.

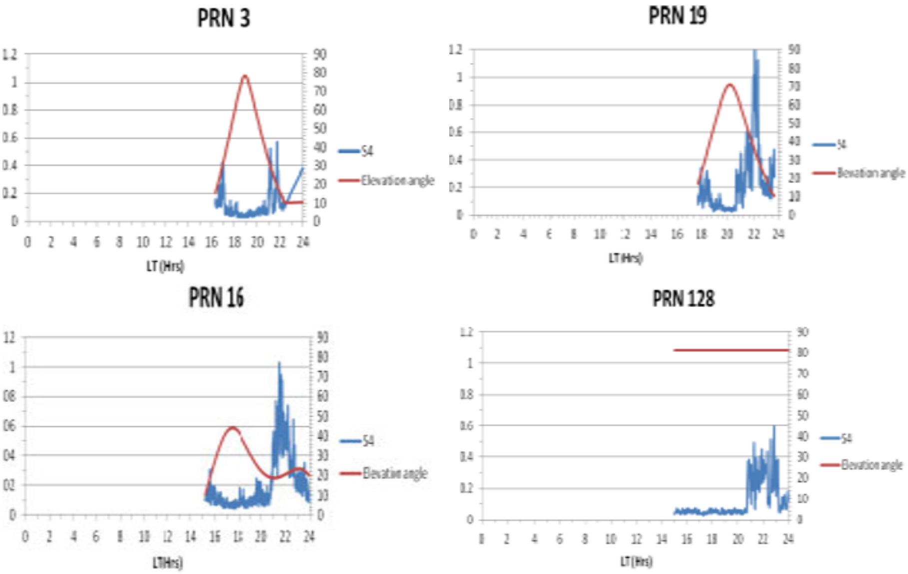


Fig. 4. Plots of elevation angles and scintillation index against the local time for some satellites in view of the GPS receiver on 25 October 2011.

4. DISCUSSION

From Figs. 1 and 2, scintillations are observed during post-sunset hours, decaying around midnight. We attributed the post sunset occurrences of scintillations to ionospheric density, largely dependent on the electric field, recombination rate and the neutral winds (Titheridge 1995, Akala *et al.* 2014). During the period of local sunset in the equatorial region, the zonal neutral wind and the rapid decay of the E region density interact to develop an enhanced eastward electric field on the day-side of the terminator and a westward electric field on the night-side (Rishbeth *et al.* 1963, Woodman 1970, Kelley 1989, Anderson and Haerendel 1979, Heelis 2004).

The enhanced eastward electric field (pre-reversal enhancement, PRE, in the zonal electric field) causes vertical upwelling of the F region and steepens the bottom side density gradient to trigger the Rayleigh–Taylor instability (Kelley 1989). Consequently, the low density plasma from the bottom side percolates into the topside ionosphere to develop a plethora of plasma bubbles that transform to a cascade of irregularities of different scale sizes and cause scintillation of radio signals (Basu *et al.* 2002, Valladares *et al.* 2004, Akala *et al.* 2012, 2014).

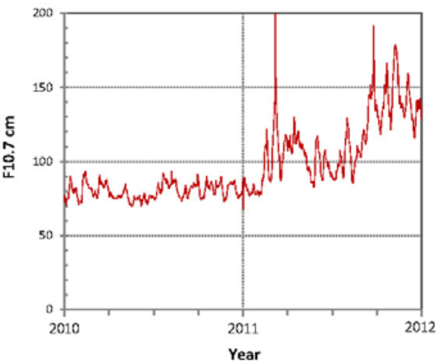
The seasonal variations in ionospheric scintillations can be attributed to the fact that occurrences are predominant during the periods when alignment of the solar terminator with the geomagnetic meridian is closest (Tsunoda

1985). The seasonal variation can also be explained in terms of the effect of variation of pre-reversal enhancement (PRE) of the eastward electric field (Mukherjee *et al.* 2012).

The depth of scintillation that radio signals experience is directly related to the level of fluctuations in the plasma density or the integrated electron density deviation along the ray path (Chatterjee and Chakraborty 2013). As shown in Fig. 4, at high elevation angles, satellite signals suffer less scintillation events, in comparison to low elevation angles, where scintillations are more predominant. The observed decrease in scintillation activity at the high elevation angles can be attributed to reduction in slant length of the receiver from the satellites (Oron *et al.* 2013). This is due to the fact that variations in the electron contents along the satellite signal path leads to formation of irregularities closely associated with scintillation activity along the ray path.

As shown in Figs. 1 and 2, scintillation is solar activity dependent. Scintillations were more numerous in 2011 than 2010. The increase in scintillation event with increasing solar activity may be attributed to increase background ionization in the ionosphere resulting to the formation of more irregularities, which in turn increases scintillation activity as solar activity progresses (Olwendo *et al.* 2010). Figure 5 shows daily F10.7 cm solar radio flux and daily sunspot number for 2010 and 2011. The implication of this is that the sun was far more active in 2011 than 2010, translating to more background ionization in 2011 than 2010.

From the standpoint of pre-reversal enhancement (PRE) of electric field, more PREs were recorded in 2011 than 2010, based on the fact that the background ionization density was greater in 2011 than 2010. Fejer *et al.* (1979) using the incoherent scatter radar measurements, concluded that during solar maximum years, the evening pre-reversal enhancement (PRE) is



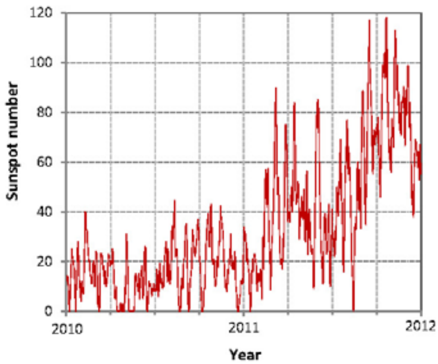


Fig. 5: (a) Plot of F10.7 cm solar flux for 2010 and 2011, (b) Plot of sunspot number for 2010 and 2011.

observed throughout the year, but with least amplitudes during May to August, and these amplitudes increases with solar activity. Additionally, as solar activity descends, the height of the F-region decreases, leading to sparse generations of irregularities, and by extension, scintillation occurrences (Mukherjee *et al.* 2012).

Geomagnetic storm occurrences appear to beef-up background ionization density of the ionosphere. Consequently, the 25 October 2011, geomagnetic storm might have enhanced ionospheric background ionization density, leading to more irregularities and scintillations, compared to a quiet day (14 October 2011) when no scintillation activity was recorded. With a view to establishing a firmer conclusion, in our future efforts, we hope to investigate the dependence of African equatorial scintillations on geomagnetic storms, using large data sets (2009-2014) from three or more GPS stations.

5. CONCLUSION

We characterized GPS amplitude scintillations over Kampala, Uganda, in the East Africa longitudinal sector, using 2010-2011 data. Over Kampala, ionospheric scintillation is a post sunset event beginning after sunset and decaying toward the midnight. The interaction of zonal neutral winds with rapid decay of E region density might have led to the development of enhanced eastward electric field to trigger Rayleigh–Taylor instability, causing ionospheric irregularities.

On monthly basis, October and April had the highest percentage of occurrence of scintillation, while January and June recorded the least. Seasonally, equinoxes recorded highest occurrences of scintillation, while June solstice recorded the least.

The angle of elevation of the satellite signals traversing ionospheric irregularities is an important factor that determines the extent of scintillation that the signals will experience. Signals from satellites at low elevation angles are susceptible to multipath effects than those at high elevation angles. Signals impairments at high elevation angles are likely to be due to the presence of ionospheric irregularities along the path of the signals.

Furthermore, scintillation occurrences showed solar activity and geomagnetic activity dependence. The numbers of satellites that experienced scintillations were greater on a storm day, compared to a quiet day. We attributed this to increase in background ionization density, occasioned by the geomagnetic storm occurrence.

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